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LIFE CYCLE MANAGEMENT

Integrating environmental and economic life cycle analysis in product development: a material selection case study

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Abstract
Purpose Achieving sustainability by rethinking products, services and strategies is an enormous challenge currently laid upon the economic sector, in which materials selection plays a critical role. In this context, the present work describes an environmental and economic life cycle analysis of a structural product, comparing two possible material alternatives. The product chosen is a storage tank, presently manufactured in stainless steel (SST) or in a glass fibre reinforced polymer composite (CST). The overall goal of the study is to identify environmental and economic strong and weak points related to the life cycle of the two material alternatives. The consequential win–win or trade-off situations will be identified via a life cycle assessment/life cycle costing (LCA/LCC) integrated model.
Methods The LCA/LCC integrated model used consists in applying the LCA methodology to the product system, incorporating, in parallel, its results into the LCC study, namely those of the life cycle inventory and the life cycle impact assessment.
Results and discussion In both the SST and CST systems, the most significant life cycle phase is the raw materials production, in which the most significant environmental burdens correspond to the Fossil fuels and Respiratory inorganics categories. The LCA/LCC integrated analysis shows that the CST has globally a preferable environmental and economic profile, as its impacts are lower than those of the SST in all life cycle stages. Both the internal and external costs are lower, the former resulting mainly from the composite material being significantly less expensive than stainless steel. This therefore represents a full win–win situation. As a consequence, the study clearly indicates that using a thermoset composite material to manufacture storage tanks is environmentally and economically desirable. However, it was also evident that the environmental performance of the CST could be improved by altering its end-of-life stage.
Conclusions The results of the present work provide enlightening insights into the synergies between the environmental and the economic performance of a structural product made with alternative materials. Furthermore, they provide conclusive evidence to support the integration of environmental and economic life cycle analysis in the product development processes of a manufacturing company or, in some cases, even in its procurement practices.

Keywords Composite materials · Externalities · Life cycle assessment · Life cycle costing · Life cycle thinking · Product development · Stainless steel · Storage tank

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1 Introduction

Pressure, either from legislation or public opinion, has been mounting on companies to apply the so-called sustainable development approach to their activities and products. The development that "meets the needs of the present without compromising the ability of future generations to meet their own needs", firstly introduced by the Brundtland report, is

the most well-known definition of sustainable development (WCED 1987). Sustainable development includes environmental, economic and social aspects, known as the three-pillar model (adopted in the Rio de Janeiro Summit in 1992, as described in Klöpffer 2008). These components have to be properly assessed and balanced when a new product or process is to be initiated or an existing one is to be improved. This should be the ultimate objective of product development (Klöpffer 2003, 2008). A vision of a world well on its way to sustainability by 2050 was developed by the World Business Council for Sustainable Development (2010). In this world, the global population, which should have stabilised at 9 billion by 2050, will live well and within the limits of the planet. That is, with a standard of living that can be sustained with the natural resources available and without further harm to biodiversity, climate and the ecosystems. The pathway to achieve this includes incorporating the cost of externalities (starting with carbon, ecosystem services and water) into products and services. For that, decreased carbon emissions through a shift to low-carbon energy systems, highly improved demand-side energy efficiency and better use of resources and materials must be achieved. This 2050 vision therefore challenges companies to rethink their products, services and strategies.

As a consequence of the above, the integration of environmental and economic criteria with the traditional requirements in product design is gaining vital importance for many companies (Ribeiro et al. 2008; Peças et al. 2009; Alves et al. 2009; Simões et al. 2010, 2012b). It is well known that environmental impacts, as well as future cost and revenues of products, originate to a high extent in the design phase (Seo et al. 2002; Asiedu and Gu 1998; Rebitzer et al. 2003; Hauschild et al. 2005). The research and development (R&D) phase, which precedes or incorporates the design phase, is key to manufacture cost-efficient products with minimal environmental impact, resource consumption and emissions (Rebitzer et al. 2003). Therefore, environmental and economic constraints should be integrated as early as possible in the product development process as optimisation parameters. This is part of the sustainable development approach, which uses several methods and tools to analyse life cycle (LC) interdisciplinary interactions (Klöpffer 2003, 2008; Zamagni 2012). Amongst them are life cycle assessment (LCA) (ISO 14040 2006; ISO 14044 2006) and life cycle costing (LCC) (Ciroth et al. 2008; Swarr et al. 2011) that take into account the full LC, from raw material extraction, production to use and final disposal, in a systemic approach. Only one such approach allows recognising and addressing conflicting trade-offs that arise when selecting alternative materials or products (Klöpffer 2003, 2005, 2008; Norris 2001; Zamagni 2012). Studies on the application of LCA to product development (Keoleian 1993; Bhander et al. 2003; Hauschild et al. 2004; Millet et al. 2007; Nakano and Hirao 2011) suggest that several limiting factors exist, due to organisational and operational constraints, such as temporal and spatial relationships between physical and information flows. The usefulness and scope of this application will also be influenced by the product nature and complexity, the availability of technical and financial resources and the design approach itself. A study by Millet et al. (2007) suggests that in product design LCA should be considered as a specialised tool, to be handled by a specific player (the LCA practitioner). In fact, the interpretation of its core results requires high levels of environmental knowledge that designers usually do not have (Bhander et al. 2003). Therefore, the LCA practitioner and the designer must co-exist and collaborate to overcome the knowledge gap between them, interacting with other company partners and stakeholders (Nakano and Hirao 2011). The argument that a LCA study needs a substantial amount of information in the early stages of product development (the phase that has higher potential for environmental gains), information that is then not available, is well known (Millet et al. 2007; Nakano and Hirao 2011). However, a detailed LCA is not necessary in that stage, since the product is only roughly defined, its final features not yet known. In fact, in this phase, a simplified LCA of different product concepts (product family) and life scenarios should be performed to analyse their environmental impacts and identify potential environmental hot spots. In this way, further design changes can be implemented at a later stage, but the fundamental options have already been made (Hauschild et al. 2004). Specifically, at the design stage, the data gaps can be overcome by using LCA inventory databases (Nakano and Hirao 2011). Although still evolving, the LCA methodology, as well as economic analysis, have already been integrated in product development process, using different approaches (Nakano and Hirao 2011; Bovea and Vidal 2004; Kicherer et al. 2007; Huo and Saito 2009; Simões et al. 2012a; Allacker 2012). This is consistent with the LCA intrinsic transdisciplinary nature (Zamagni 2012). For example, Nakano and Hirao (2011) proposed a supply chain collaboration model for collecting producer-specific LCA data from business partners. In a production process, this allows collecting flow data that can be used in LCA reporting and cost accounting, therefore contributing for its environmental and economic improvement. Boeva and Vidal (2004) suggested a model that combines the LCA, LCC and contingent valuation. This model allows the identification of alternatives that reduce environmental impact and the external cost of the product, while maximising its value.

More than 160,000 materials are currently available to the engineer for the design and manufacturing of products for many applications (Ashby 2011). When designing a product, the engineer has to consider a list of properties (e.g. mechanical, chemical, haptic, etc.) in order to choose the material which best suits the intended application. In the past, metals and alloys have been the dominating materials in engineering components. Currently, polymers are increasingly replacing

them because they present a combination of properties which are more attractive to the engineer (e.g. light weight, corrosion resistance, versatility, etc). Further to this, polymers are easy to process, meaning that they can be processed at relatively low pressures and temperatures. Although not as widespread, ceramics are also an emerging class of advanced engineering materials. Finally, the engineer can combine the best properties of most of these materials to make composites (Ashby and Jones 1996). A composite material is formed by combining two or more constituents, which remain distinct at macroscopic level, while promoting a synergic effect on the global properties. In general, there is a continuous phase, the matrix, in which the reinforcing element (fibres or particles) is incorporated (Nunes et al. 2003). Due to the abovementioned characteristics, polymers are potential candidates for composite matrices. However, as their mechanical properties (relatively low strength and stiffness) are not particularly suitable for structural applications, the combination with reinforcements is particularly interesting. Elastomers, thermosets and thermoplastics, and different types of fibres (e.g. glass, carbon and aramid) can be used as matrices and reinforcements, respectively. Currently, composites are widely used in various products and industries, e.g. automotive components, sport and consumer goods, aerospace parts and in the marine and oil industries (Mazumdar 2002). Several LC studies show the interest of using composites in the automotive industry, evidencing that the use phase is the determining factor of the environmental load (Schmidt 2003; Roes et al. 2007; Schwab-Castella et al. 2009; Song et al. 2009; Khanna and Bakshi 2009). This is largely due to the lower energy (fossil fuels) consumption during this phase, which is directly associated to the weight of the vehicle. By replacing traditional materials (such as steel) with polymer composites, the environmental impact can be diminished through weight reduction. On the other hand, the use of polymer composites increases the production cost. Thus, it is the trade-off with energy savings in the use phase that enables an overall LC cost reduction. Adoption of composite technologies in the automotive industry also brings economic advantages due to production volume (Fuchs et al. 2008). Unlike the automotive industry, the use of composites' structures in the construction sector does not bring obvious beneficial consequences in the use phase. Additionally, construction structures generally do not have the mass production cost advantage but are instead custom-designed (Schwab-Castella et al. 2009). Some studies, albeit only a few and limited in scope, have investigated this topic. For instance, a study on pavements evidenced that those reinforced with composites have lower environmental loads than if reinforced with steel (Katz 2004). This mainly results from the absence of maintenance of the composite (contrarily to steel that undergoes corrosion) and from the reduction in the use of other materials (cement and concrete) due to design aspects.

It is thus clear that research is still required to better understand the environmental and economic loads associated with different structural design solutions for static (non-mobility) applications. In a preceding work, the authors have already addressed this topic, by applying a LCA/LCC integrated model to compare the performance of steel, aluminium and composite lighting columns (Simões et al. 2012a). In this context, the present work consolidates the previous LCA/LCC model and expands it to a larger number of impact categories, comparing two possible material selections for a different structural product. A storage tank, currently manufactured in stainless steel (SST) or in glass fibre-reinforced polymer composite (CST), was the product selected. The overall goal of this study is to identify strong and weak points related to the LC of the two alternative tank systems. The results provide enlightening insights into the synergies existing between the environmental and economic performances of both systems. Motivating companies to rethink their products, services and strategies by integrating environmental and economic LC analysis in their product development processes or, in some cases, even in their procurement practices, is another goal of the work.

2 Methodology

The LCA/LCC integrated model (Simões et al. 2012a) implemented in this work consists in using, in parallel, the LCA and the LCC methodologies, according to the ISO 14040 series (ISO 14040 2006; ISO 14044 2006) and the Ciroth et al. and Swarr et al. guidelines (Ciroth et al. 2008; Swarr et al. 2011), respectively. The model applies the LCA methodology to the product system and, concomitantly, incorporates the results into the LCC study, namely the life cycle inventory (LCI) and life cycle impact assessment (LCIA) (Fig. 1). This allows the flows of materials, energy and emissions to be directly quantified. The goal and scope phase of the LCC should be consistent with that of the LCA. The main issue to consider is the use of the same functional unit and system boundaries in both methodologies. However, in the LCC, it is also necessary to define the perspective, time reference and discount rate and to select the economic aspects and type of analysis (conventional, environmental or societal) that will be done.

3 Life cycle assessment

A storage tank's function is to store treated water before distribution (Bhardwaj 2001). The system studied (Fig. 2) is a tank to hold drinking water at atmospheric pressure, made in composite or in stainless steel. These two materials can be used in this application due to their resistance to corrosion

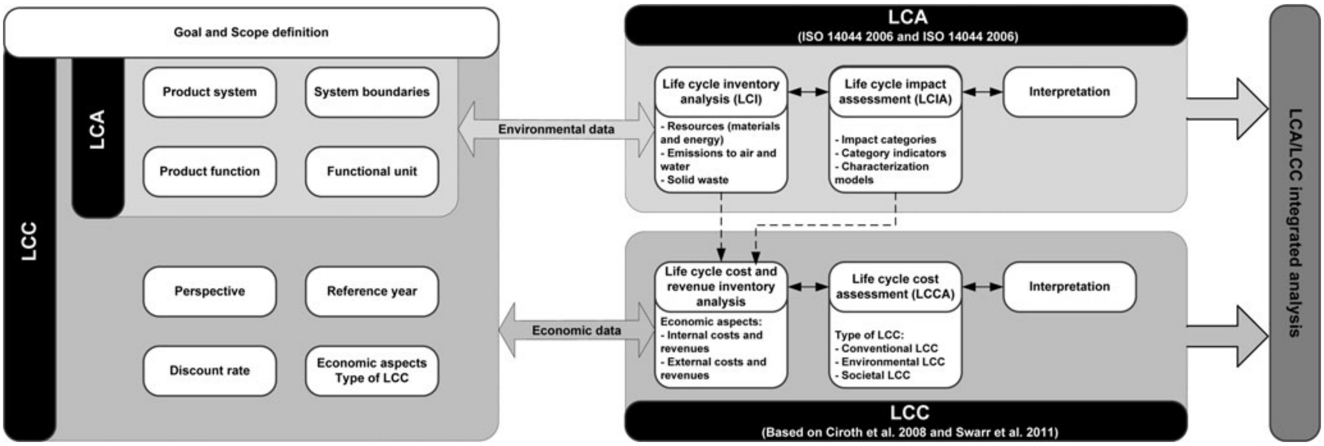


Fig. 1 LCA/LCC integrated model framework

when in contact with moisture or water, contrarily to ordinary steel. The storage tank consists of a cylindrical body and the corresponding top and bottom. Accessories, such as supply and drain connections, suspension eyebolts, vent pipe, liquid level indicator and man hole were also included in the analysis. Adjacent processes and materials, such as water pumps, piping supply, valves, energy to pump water and the water used during the whole LC, were excluded, because they are the same for the two systems. There are several possible alternative holding capacities (volume), positions (vertical or horizontal) and top and bottom configurations for a storage tank. A vertical tank with a holding capacity of 30 m^3, convex (or conic) top and a flat bottom was selected for this study. Data from two important Portuguese manufacturers (that work with composites and stainless steel), as well as the experience collected directly therein, provided the necessary input for the study. The tanks' lifespan depends on the construction material and local weather conditions (e.g. salty sea air). However, the real lifespans of these products are not yet completely known. Both manufacturers' experience is that their tanks lifespan is longer than 30 years. They do not know of any case where it was necessary to substitute a tank due to material damage in that period. Therefore, a 30-year lifespan was assumed for both tanks. In any case, due to the material properties, the lifespan of the CST is estimated to be more than 50 years and, for the SST, around 80 years. Accordingly, a storage tank with holding capacity of 30 m^3 of drinking water at atmospheric pressure, and a lifespan of 30 years was defined as the functional unit. The characterisation of both tank systems is presented in Table 1. The amount of material needed was determined on the basis of their lengths, diameters and material thicknesses. The LCA of the two systems is based in a "cradle-to-grave" assessment which considers the raw materials production, tank production, on-site installation, use and maintenance, dismantlement and end-of-life (EoL) treatment and all intermediate transport processes. It is supposed that no maintenance is needed for both tanks during the use phase. The R&D, installation and dismantlement LC phases

Fig. 2 Schematic of a storage tank studied in this work (functional unit). Key: *1* cylindrical body, *2* top, *3* bottom, *4* supply connection, *5* drain connection, *6* liquid level indicator, *7* vent pipe, *8* man hole, *9* suspension eyebolts

Table 1 Characterisation of the storage tanks

Properties	CST	SST
Material	Polyester resin +glass fibre	Stainless steel AISI 304 L
Surface treatment	Gel coat	2B finishing
Colour	Client specification	Natural colour of the stainless steel
Lifespan	30 years	30 years
Maintenance	No	No
Full height	4,520 mm	5,100 mm
Internal diameter	3,000 mm	2,865 mm
Wall thickness	7.6–9.5 mm	2.5 mm
Total volume	30 m^3	30 m^3
Total weight	948 kg	1,400 kg

are excluded from the study, as again they were considered to be equal for the two systems.

The CST is made of 53 % glass fibre mats and rovings, 45 % unsaturated polyester resin and 2 % stainless steel. The tank consists of three main parts: a cylindrical body ("Virola"), a flat bottom and a convex top. These parts are welded together, and then accessories, some of them in stainless steel (screws, suspension eyebolts, etc.), are applied to finish the storage tank. The cylindrical body is manufactured by filament winding. The flat bottom, convex top and some accessories are produced by hand lay-up. During the body curing process, heaters are employed to elevate the environment temperature. On the other hand, the flat bottom, convex top and accessories are cured at room temperature. After curing, the parts are released from the mould. To facilitate that, a release agent is initially placed on the surface of the mould. The ends of the parts are trimmed of excess flash, sanded and drilled if necessary, producing about 1 % of waste. The waste, classified as non-hazardous industrial waste, is grinded and stored until it is sent to an EoL facility to be properly treated (landfill). After all the parts are finished, they are manually welded together by hand lay-up. As the constitutive unsaturated polyester resin is colourless, a coloured polyester gel coat is applied after all parts are assembled, to achieve the final colour specified by the client. At this stage, the storage tank is ready to be stored and shipped out and transported by truck to the site where it will be installed. In this study, it was considered that it was sent to a client in the south of Portugal (Algarve). This is the largest possible distance the tank could travel inside the country, considering the location of the manufacturers' facility (in Maia, at the north of Portugal). The obsolete CST is transported by truck to an EoL facility to be properly treated. It is supposed that the EoL treatment is the same of the production waste, that is, the tank is sent to the nearest landfill. The stainless steel accessories are separated and sent for recycling.

The SST is made of stainless steel only. Similarly to the CST, it has three main parts that are welded together, and then accessories are applied to finish the process. The various parts, including some accessories, are produced by rolling, cutting, welding (tungsten inert gas (TIG) or metal active gas welding (MAG)) and border forming. These manufacturing steps produce circa 1 % of stainless steel waste that will be collected and used as scrap (recycled). After all the parts are made, they are welded together (again by TIG or MAG) and accessories applied to manufacture the finished storage tank. Each weld is washed with an acid pickling (a mixture of nitric and hydrofluoric acid), to remove scaling and heat tints from the parent surfaces. After the final assembly, the storage tank is washed with a degreasing detergent. At this stage, it is ready to be stored and shipped to the client. As with the CST, the SST will be transported by truck from the manufacturer (in Vale de Cambra, at the centre of Portugal) to the installation site. Again, it is considered that the client is located in the Algarve. The obsolete SST is transported by truck to the EoL facility that in this study is considered to be a metal recycler. The SST is relatively simple to recycle, since stainless steel is easily collected and treated in existing process streams (Johnson et al. 2008). In both systems, the stainless steel recycling is modelled considering that production of new stainless steel is avoided.

The systems have been modelled using commercial databases (Ecoinvent 2007; BUWAL 1996; IDEMAT 2001) and also field data, which were ultimately summarised in the LCI that was performed in SimaPro 7 (SimaPro 2011). The LCIA was performed using the Eco-Indicator 99 (EI99) method (Goedkoop and Spriensma 2001). The EI99 is a damage-oriented method that considers 11 environmental impact categories and is often used by LCA practitioners. The impact categories are combined and quantified in 3 damage categories (Resources, Ecosystem quality and Human health). It is well known that the selection of the impact method can have profound consequences in the results of a LCA study (Simões et al. 2011). Ultimately, a single score can be obtained through aggregation of these damage categories by means of weighting factors. In the present study, normalisation and weighting were performed at damage category level, and European values were adopted.

The LCIA characterisation results of the main LC phases of the CST and SST are shown in Figs. 3 and 4, respectively. The characterisation results of the CST system (see Fig. 3) reveal that the raw materials production (glass fibre, unsaturated polyester resin and stainless steel) has the highest emission values in all environmental categories, except Carcinogens and Radiation. In this case, the main contributor is the CST production phase. The high impact of the raw materials production stage is due mainly to the energy intensive process used in the glass fibre production. The EoL phase has a positive environmental impact in some categories (Respiratory inorganics, Climate change, Acidification/Eutrophication, Land use, Minerals and Fossil fuels), due to the avoided emissions resulting from the recycling of stainless steel. For the SST system, the characterisation results (Fig. 4) show that the raw material (stainless steel) production is again the more significant LC phase, portraying the highest emission values in most impact categories. Exceptions are the Carcinogens, Radiation and Ecotoxicity categories, in which the main contributor is again the SST production phase. Once more, the EoL phase has a positive impact in almost all environmental categories (except Carcinogens, Radiation, Ozone layer and Ecotoxicity). This is also due to the avoidance of emissions resulting from the recycling of stainless steel. Although the

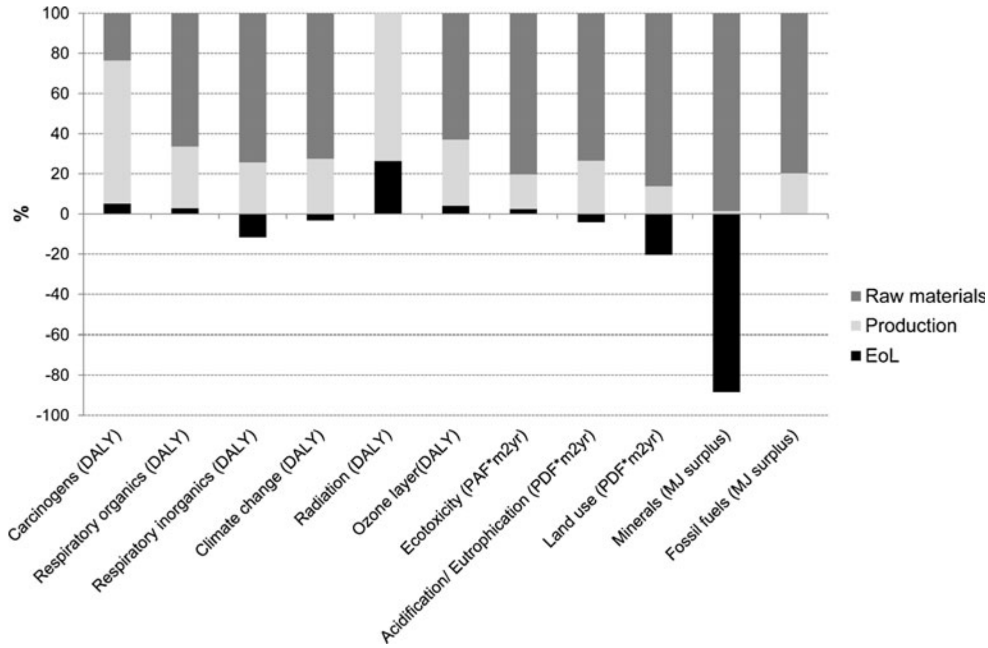


Fig. 3 LCIA characterisation results of the CST system. *DALY*: disability adjusted life years (years of disabled living or years of life lost due to the impacts); *PAF*: potentially affected fraction (animals affected by the impacts); *PDF*: potentially disappeared fraction (plant species that disappear as result of the impacts); *MJ surplus*: surplus energy (MJ) (extra energy that future generations must use to extract scarce resources)

production of stainless steel requires a considerable amount of minerals such as iron, chromium, nickel and manganese, which contributes to the Minerals category, and consequently to the Land use category, its recycling compensates almost 90 % of these environmental impacts.

The comparative LCIA characterisation and normalisation results of the LC of the two systems are shown, on a functional unit basis, in Figs. 5 and 6, respectively. The SST depicts the worse environmental profile (see Fig. 5), with higher values in all environmental impact categories. The normalisation results (see Fig. 6) show that the Fossil fuels and Respiratory inorganics categories represent the most significant burdens, in terms of scale of contribution in both tank systems. The SST also presents significant environmental burdens regarding Climate change. The higher impact of the SST in the Respiratory inorganics, Fossil fuels and Climate change categories is due to the energy intensive process used in its raw materials production. The amount of material necessary to make the storage tank is also higher (more 32 % in weight), leading to a higher load to transport and consequently to higher fossil fuel consumption and gaseous emissions.

The controversy about subjective factors affecting the weighting step in LCA, namely the calculation of a single score, is far from over, in spite of its usefulness in conveying

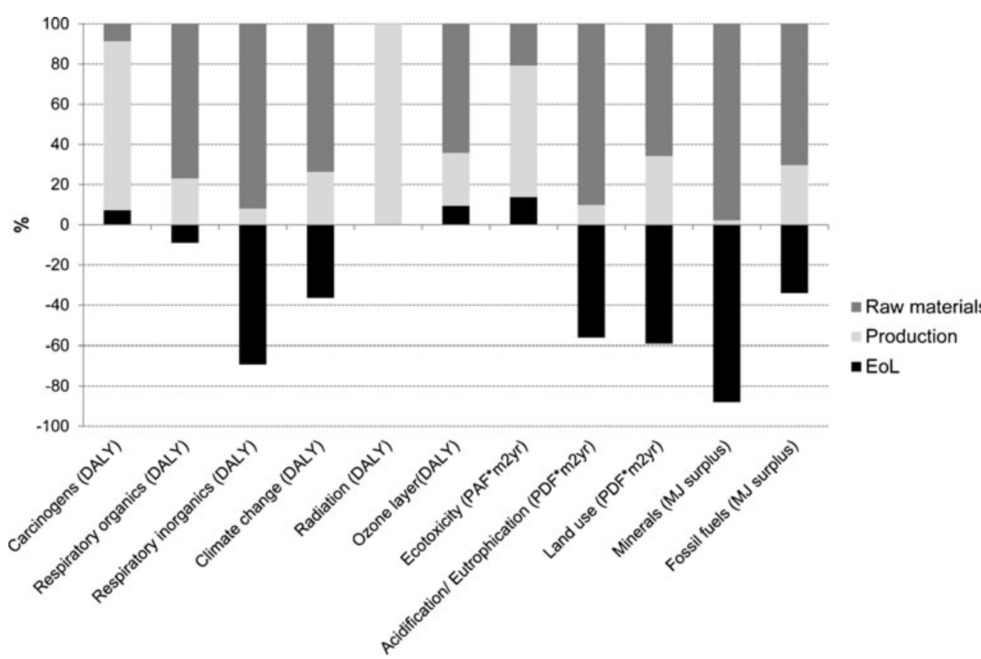
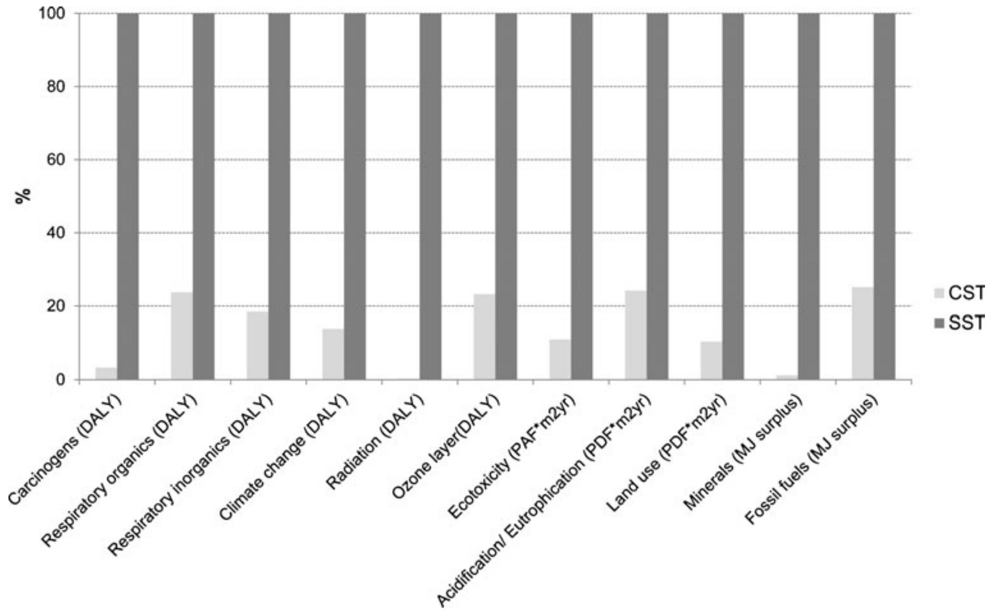


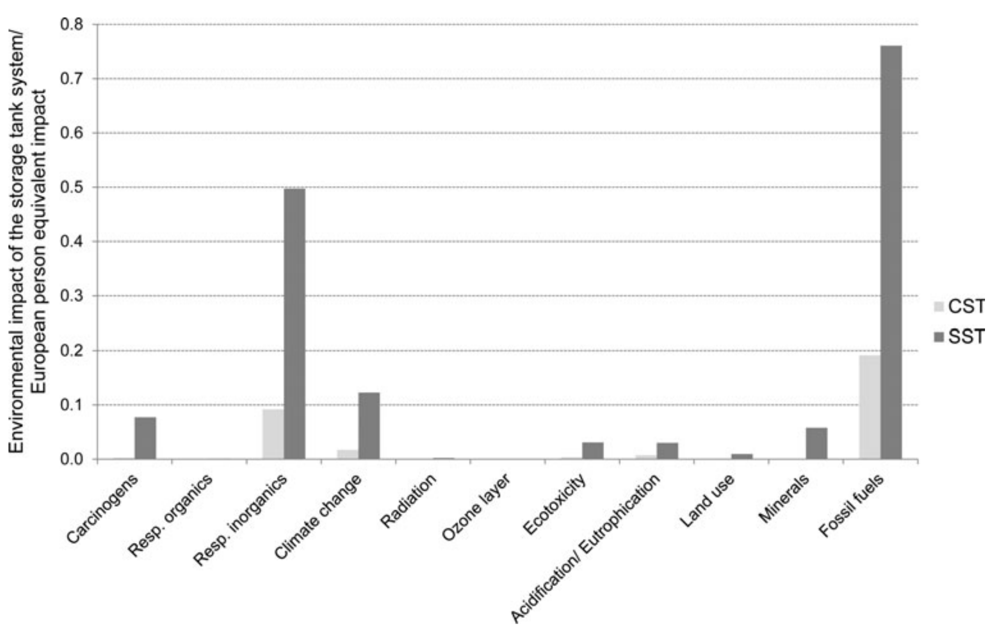
Fig. 4 LCIA characterisation results of the SST system

Fig. 5 Comparative LCIA characterisation results of the two storage tank systems



a clear message to the stakeholders. To unmistakably rank the product alternatives, this step was performed in this study using the EI99 hierarchist (average weighting set) method. The single score results obtained (expressed in Eco-Indicator points (Pt)) are quite distinct, 87.8 Pt and 472 Pt, for the CST and SST, respectively. In comparative studies, the concept of a "mixing triangle" introduced by P. Hofstetter and co-authors (Hofstetter et al. 1999) has the potential to somewhat circumvent the abovementioned controversy. It defines weighting factor domains (corresponding to the three damage categories: Resources, Ecosystem quality and Human health) in which the single score indicator of one alternative prevails over the other. In this way, it transformed the interpretation of the single score into a consensus analytical process instead of one that generates single truths (Simões et al. 2013). However, in the present case, the planar representation of the mixing triangle would be useless, as it would depict a figure with a single colour, since one alternative prevails over the other for all weighting sets. Nevertheless, a three-dimensional representation of a "single score surface" as a function of the damage categories weighting sets (only two damage categories are needed as the third is the complement to 100 %) can still be of interest. Indeed, it can provide, by simple visual inspection, an idea of how the single scores of the two tanks are positioned for all weighting factors. Single score surfaces were thus calculated for both the CST and SST and represented in a three-dimensional plot using the software package MATLAB (2010). The results are shown in Fig. 7, which makes clear that the

Fig. 6 Comparative LCIA normalisation results of the two storage tank systems



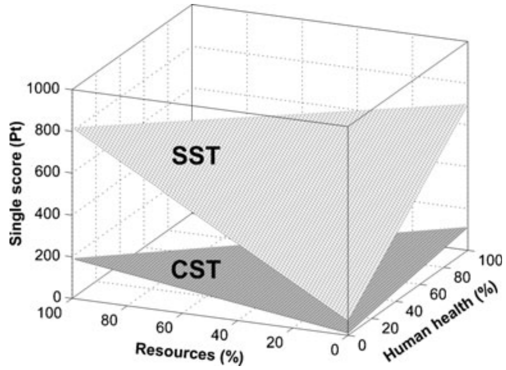


Fig. 7 Single score surfaces of the SST and CST systems for the three EI99 method damage categories (the Ecosystem quality damage category is the complement to 100 %)

single score surfaces do not intersect. Moreover, the slopes of the two surfaces are different, suggesting that the SST is more sensitive to the selected damage category weighting set. In addition, the plots show that the difference between CST and SST is considerably higher when Human health and Resources are given higher importance than the Ecosystem quality damage category.

As mentioned before, the lifespan of both tanks is yet not fully known and was assumed to be equal to 30 years. In reality, the CST lifespan is believed to be around 50 years. This possibility does not change the global LCA conclusions, since the SST already has higher impact in all environmental categories. Increasing the lifespan of the CST would only decrease even more its environmental impact, avoiding the consumption of new resources and emissions (Simões et al. 2012b). Furthermore, a sensitivity analysis revealed that the SST and the CST will only have the same Fossil fuels, Respiratory inorganics and global (single score) environmental impacts, if the lifespan of the former was 4, 5.5 and 5.4 times that of the latter, respectively. Some sources consider that the SST could have a lifespan of up to 80 years. This possibility again does not change the global LCA conclusions, as, for example, the lifespan of the SST should be at least a 120 years for it to have the same impact as the CST in terms of Fossil fuels.

One significant difference, however, can occur if the CST composite parts would have a different EoL treatment. In some regions of Portugal, it is possible to send a composite to incineration with energy recovery. Therefore, an alternative scenario was analysed (Fig. 8), assuming this EoL treatment for the CST and keeping the same EoL for the SST. It can again be concluded that the incineration scenario does not change the global LCA conclusions, since the SST still has higher impacts in all environmental categories. Moreover, the CST Fossil fuels environmental impact would decrease 13 %, due to the energy recovered from the incineration of its matrix. Conversely, the Climate change environmental impact increases 59 %. This is consistent with previous studies (Arena et al. 2003; Björklund and Finnveden 2005) that showed environmental savings in non-renewable resources (crude oil, natural gas and coal), as well as increases in greenhouse emissions, when incinerating plastics with energy recovery.

4 Life cycle costing

In the integrated LCA/LCC model employed in the present work, the goal and scope of the LCC study for both tank systems is consistent with the goal and scope of the LCA. Therefore, the functional unit, system boundaries and other assumptions were the same as in the latter study. In this way, the LCC methodology can be used to identify and compare all cost drivers associated with the two systems, based on a full LC perspective (producer perspective plus implications for market success due to use and disposal costs). The cost bearer “producer” is the company that manufactures the storage tank. The final “user” of the storage tank is the client that buys it. Ultimately, the “EoL” actor is the waste manager operator. The selected reference year was 2011 and the LCC type a Societal LCC that considers internal and external economic aspects (Ciroth et al. 2008). The “polluter-payer” principle is one key argument for including external costs in LCC. Monetary valuation of externalities (environmental and social costs) is a highly complex subject, and several approaches and methodologies have been applied (Ciroth et al. 2008; Swarr et al. 2011). One well-known monetisation method is quantifying damage costs through costs due to some change, such as climate change due to CO_2 (greenhouse gas) emissions. The existence of an actual market is an important issue for an externality to be considered (Swarr et al. 2011). Therefore, externalities that are anticipated to be internalised in the decision-relevant future, such as CO_2 eq, SO_2, NO_x and fine particle emission costs, were also included in the analysis. Costs of CO_2 eq emissions were obtained from a well-established market in Europe, the Europe Emission Trading Scheme (ETS) (Point Carbon 2011). In Europe, there is no market for SO_2, NO_x and fine particle emissions, therefore their emission costs were considered as damage costs and were based on the European ExternE project (Watkiss and Holland 2000). The LC cost and revenue inventory is based on the LCI and LCIA results, and additional financial information. The collected data were adjusted to 2011 Euros (Portugal) whenever necessary. Figure 9 presents the best estimation of the cumulative total costs of the two storage tank systems on a functional unit basis. Due to confidentiality requirements of the two companies that provided information for the present study, the results are reported as “monetary units”.

The two systems show a very different potential internal LC cost, the CST one being 22 % smaller, due to the cost of

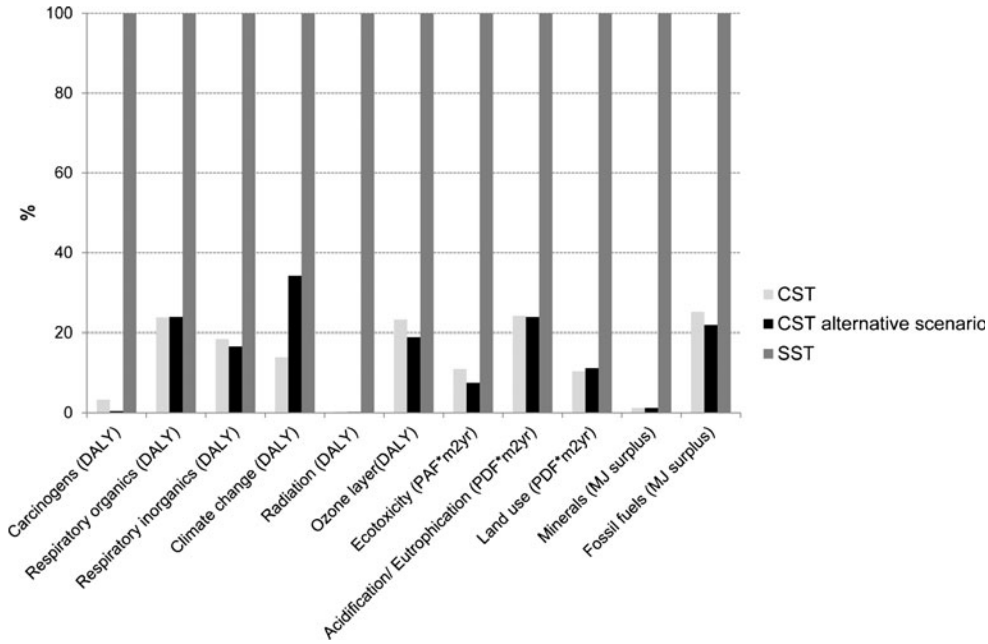


Fig. 8 Comparative LCIA characterisation results of the two systems and a CST alternative scenario

the composite material compared with stainless steel. In fact, the raw material cost is the main difference between systems. The systems depict also very different potential external LC costs, the CST being 90 % lower. The SST raw material production phase is again the main contributor to this outcome, due to the energy-intensive process used. However, the other phases also contribute, mainly as a consequence of the higher amount of material used in the production of the tank. The SST system depicts a higher SO_2 emission cost, while the CST system shows a higher NO_x emission cost, as shown in Fig. 10. In synthesis, throughout its LC, the CST presents a nearly 26 % lower total cost (internal plus external) than the SST.

Table 2 presents the best estimation of the cumulative total costs of the two storage tank systems, normalised on a yearly basis, for two alternative lifespan scenarios and the base scenario of 30 years. The assumption that CST lifespan is around 50 years does not change the global LCC conclusions, yet again for the same reasons, since the LC already has a lower total cost, increasing its lifespan would only make it more cost-competitive against the SST. If it is assumed that the CST composite parts are sent to incineration instead of landfill, the results would be even more disparate, due to the value of the recovered energy. However, the global LCC conclusions would change for a SST 80-year lifespan, since it would become economically more attractive.

Uncertainties related to the estimation of economic valuation of external costs (environmental and social) are still highly debatable (Ciroth et al. 2008; Swarr et al. 2011). Thus alternative scenarios were evaluated excluding all external costs for which there are no European market values (SO_2, NO_x and fine particle emissions), and varying the price for CO_2 eq, as this price has shown some volatility along the years (Environment Agency 2011). The price of CO_2 eq was varied between 10 and 30 €/ton CO_2 (which corresponds to the price range in the operational years of

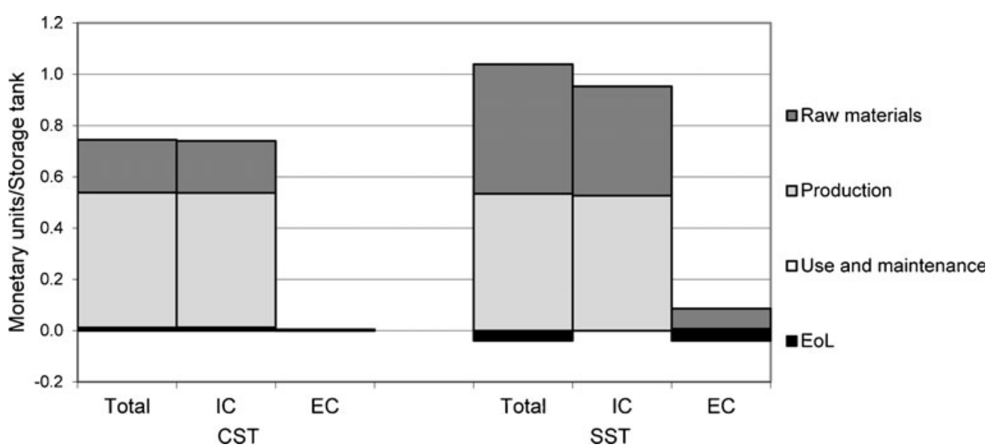


Fig. 9 Internal (*IC*), external (*EC*) and total costs of the two storage tank systems

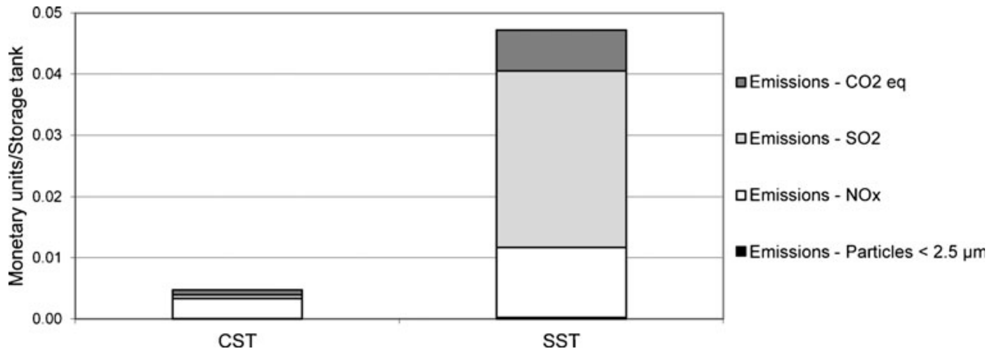


Fig. 10 External costs due to emissions of the two storage tanks

the Europe ETS market). Table 3 presents two alternative carbon price scenarios and also shows the base scenario assuming a carbon price of 11.45 €/ton CO_2; all scenarios exclude SO_2, NO_x and fine particle emission damage costs. Although these alternative scenarios change the results numerically, the global LCC qualitative conclusions would still not change, since the SST would still have a higher total cost through its LC. This is because the external costs are only a small fraction of the total cost. Indeed, in the base scenario, external costs constitute less than 5 % and 1 % of the total cost in the SST and CST, respectively.

5 LCA/LCC integrated analysis

The Fossil fuels, Respiratory inorganics and Climate change environmental impact categories were selected as the key environmental impact indicators to perform the LCA/LCC integrated analysis. This was done on the basis of the LCIA normalisation results that showed the significance of each environmental impact in terms of scale of contribution. The single score result was also selected, since it depicts the global environmental impact of both systems. Figure 11 represents, on a functional unit basis, the cumulative total costs (internal costs plus external) in combination with the LCIA results of those key environmental impact indicators, for the full LC of the two systems. In the figure, each LC stage, namely the raw material production, the storage tank production and the EoL, is represented by a line segment.

The results show that, for all key environmental/economic impact indicators, at all LC stages, there is always a win–win situation of the CST system (see Fig. 11). In fact, all the selected environmental impacts and costs are lower than those of the SST. From the figure, it is evident that the main contributor to those environmental impacts is always the raw material production stage, while the economic impact is driven by the tank production stage. The SST system only presents less environmental impact in the EoL stage, due to the avoided materials consumption and emissions resulting from the recycling of stainless steel. Globally, these data show that using a thermoset composite material in the manufacture of storage tanks would be environmentally and economically desirable. However, it was also evident that its overall environmental performance could be improved by choosing a different EoL treatment. In Portugal, to the best knowledge of the authors, CST composite parts are mostly sent to landfill. However, previous studies showed environmental savings in non-renewable resources (crude oil, natural gas and coal), as well as reduction in emissions to air (Arena et al. 2003; Björklund and Finnveden 2005) when plastics were recycled. Thermoset matrix composites are not directly mechanically recyclable, as thermoplastic ones can be. The material has to be either reduced to granules/powder by shredding or the fibres separated out of the resin matrix by combustion or chemical means. The granules/powder or the glass fibres can then be incorporated in new products as reinforcement materials. Currently, it is rarely worth recovering the glass fibres (Marsh 2001; Pickering 2006). Hence, the CST alternative EoL treatment could be incineration with energy recovery, where the inert glass fibre fraction is treated as waste and sent to landfill. Although this alternative scenario is not always

Table 2 Total costs of the storage tanks for alternative lifespan scenarios

Lifespan scenario (years)	CST (monetary units/storage tank.year)	SST (monetary units/storage tank.year)
30	0.025	0.033
50	0.015	–
80	–	0.012

Table 3 Total costs of the storage tanks for three carbon price scenarios

Carbon price scenarios (€/ton CO_2)	CST (monetary units/storage tank)	SST (monetary units/storage tank)
11.45	0.7412	0.9595
10	0.7411	0.9586
30	0.7424	0.9703

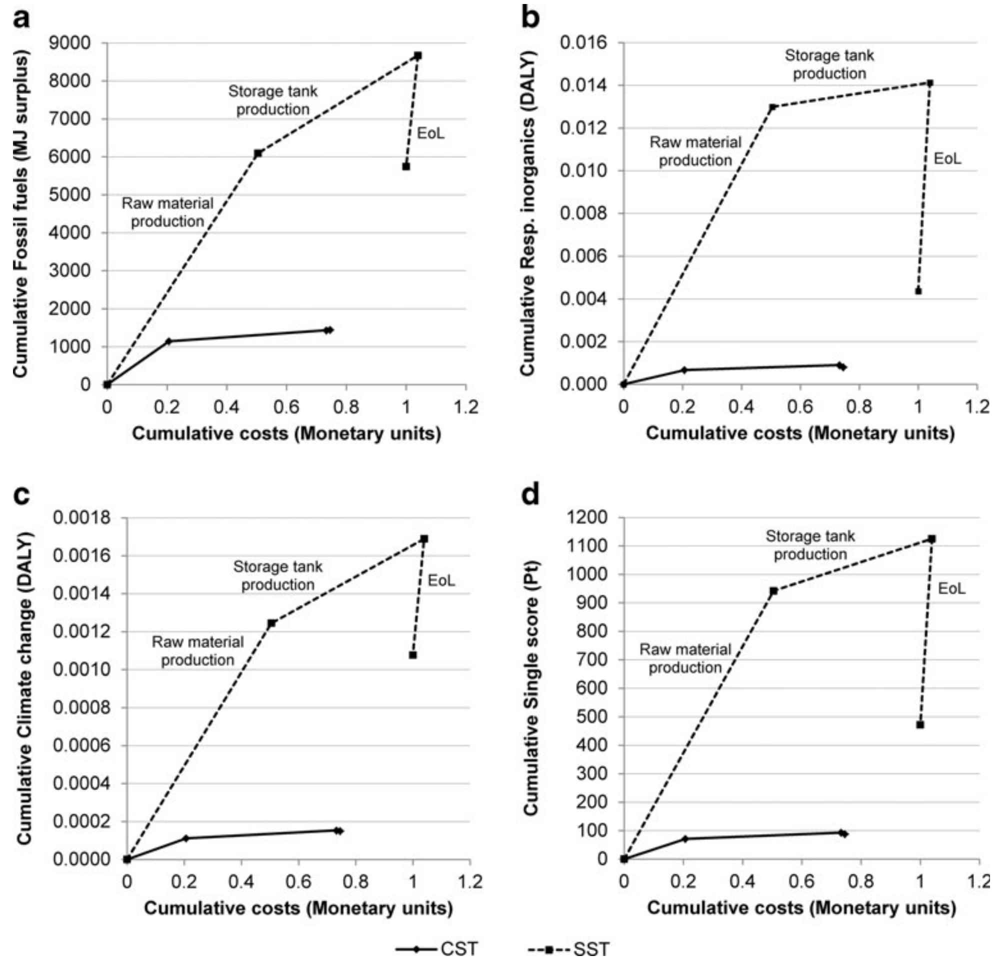


Fig. 11 Cumulative total costs versus the **a** Fossil fuels, **b** Respiratory inorganics, **c** Climate change and **d** single score environmental impact indicators for the two storage tank systems

environmental advantageous, as shown previously, it could lead to savings in crude oil resources, a major feature for the polymer industry.

6 Conclusions

The present work describes the environmental and economic LC analysis of a storage tank, comparing two possible material options: stainless steel and a glass fibre-reinforced polymer composite. It aims at better understanding the environmental and economic loads associated with different structural design solutions for static (non-mobility) applications. In fact, unlike the automotive industry, composites' structures in the construction sector do not exhibit obvious beneficial advantages due to weight reduction in the use phase. Consequently, the overall goal of this LCA/LCC integrated study is to identify strong and weak points related to the LC of the two alternative tank systems.

The LCA results show that, in both the SST and CST systems, the most significant LC phase is the raw materials production. The SST has the worst environmental profile, presenting a higher impact in all environmental impact categories. The total costs (internal plus external) of the full LC of the SST system are also higher than in the CST system. The results also show that the LC environmental performance of the CST could still be improved by selecting incineration with energy recovery as its EoL treatment. Additionally, and although not as important as internal costs, and often difficult to quantify, this work also illustrates that external costs should be considered when performing a LCC study, as they might reveal aspects not explicit in the former. One such example is the higher damage costs of CO_2 eq, SO_2, NO_x and fine particle emissions of the SST system.

The LCA/LCC integrated analysis demonstrates that the CST has globally a preferable environmental and economic profile. In all LC stages, the environmental impacts and costs of the CST system are lower than those of the SST, reflecting a full win–win situation. The main contributor to the selected environmental impacts is the raw material production stage, while the economic impact is driven by the tank production stage. It should be noted that the present study represents an extreme case, as in most comparative analyses between alternative materials, trade-offs, rather

than win–win, situations occur, at least in some of the LC stages. Its conclusions are obviously limited to the product and the specific conditions chosen. Nevertheless, they highlight the fact that polymer-based composites may have environmental and economic advantages in engineering applications that do not only depend in energy savings due to their comparatively lower weight.

A single score surface, function of the damage categories weighting sets, was used to clarify the results of the comparative LCA study of the two tank systems. To the best of the authors' knowledge, this is the first time such a three-dimensional representation that enhances the usefulness of the "mixing triangle" concept (Hofstetter et al. 1999) is reported in the literature. The three-dimensional representation of a "single score surface" has the advantage of clearly revealing the sensitivity of the alternative material solutions to the weight given to the different damage categories.

The economic sector is currently challenged to achieve sustainability. As environmental impacts and future cost of products originate to a high extent in the design phase, the integration of environmental and economic criteria in this phase is gaining vital importance for many companies. The results reported herein provide insights into the synergies existing between the environmental and economic performances of a structural product made in different materials. The LCA/LCC integrated analysis demonstrates how it is possible to minimise the overall environmental and economic impact of consumer products through the adequate selection of their constitutive materials in the design stage. It also provides arguments to motivate companies to rethink their products, services and strategies, integrating environmental and economic LC analysis in the development processes, or in some cases even in their procurement practices.

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